Lunar Navigation Satellite System (LNSS) and Its Demonstration Mission

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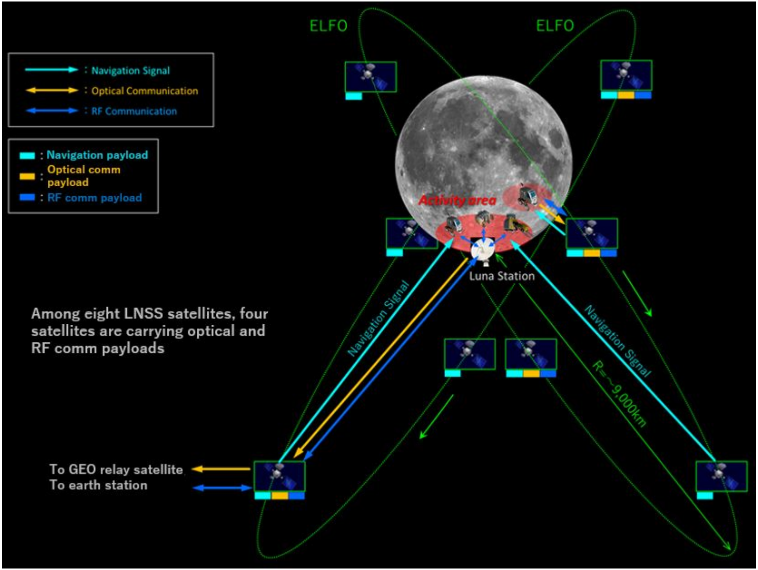
Outline

1. Lunar navigation satellite system (LNSS)
2. Mission and system overview of LNSS
3. LNSS demonstration mission
4. Upcoming related lunar programs and interoperability
5. Conclusions

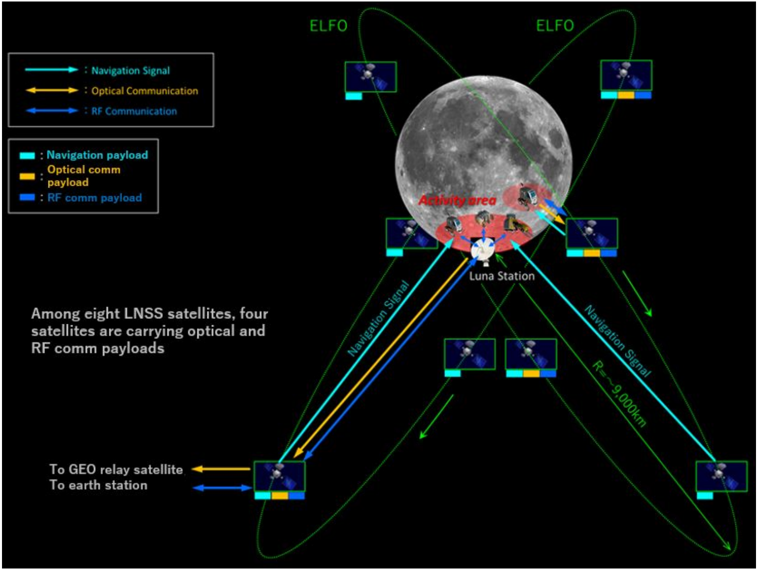
Lunar navigation satellite system (LNSS)

- GPS-like navigation satellite system for moon



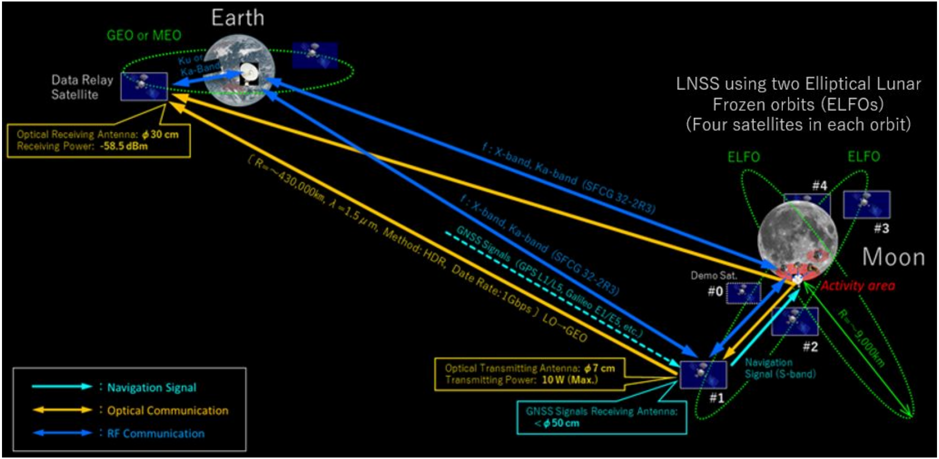
Lunar navigation satellite system (LNSS) (cont'd)

- Communication, positioning, navigation, and timing (CPNT)



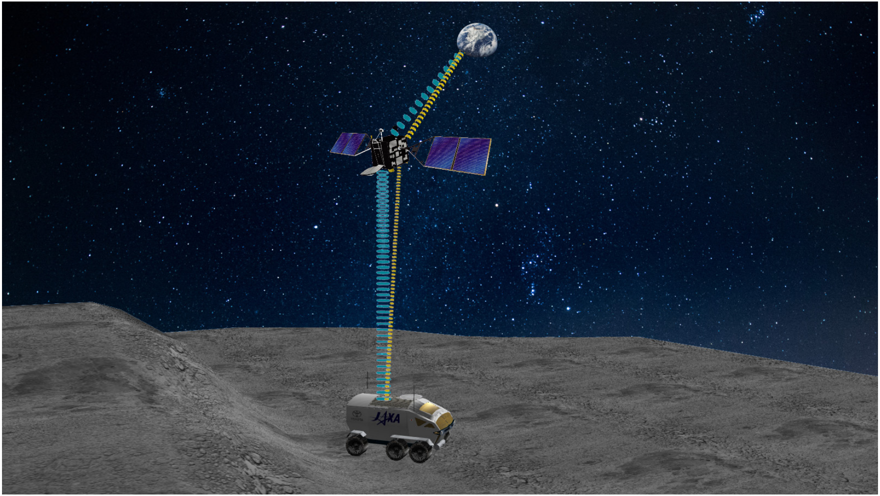
Lunar navigation satellite system (LNSS) (cont'd)

- Radio frequency and optical communication links between the moon surface user, the LNSS satellites, and the earth



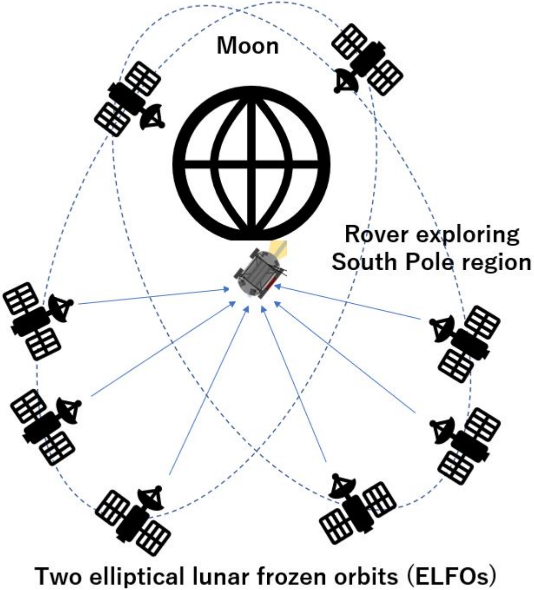
Mission and system overview of LNSS

- Helping our pressurized rover locate its own position in real-time at the lunar South Pole region



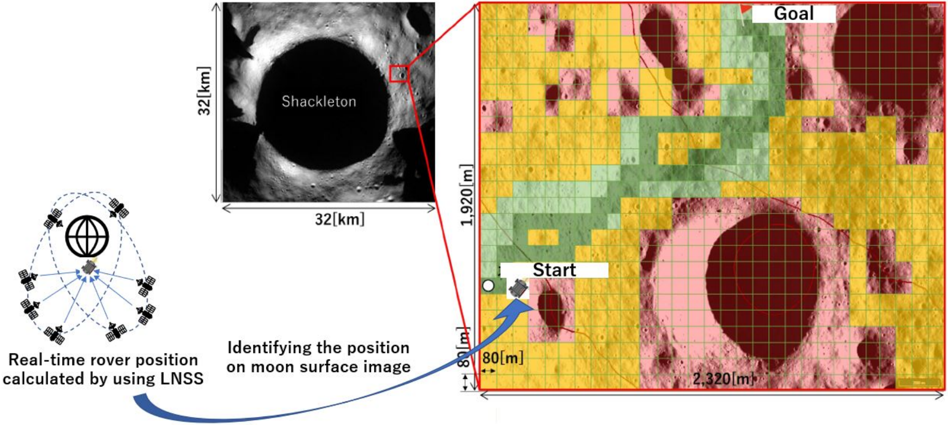
Mission and system overview of LNSS (cont'd)

- LNSS real-time positioning service for the rover



Mission and system overview of LNSS (cont'd)

- Localization of the rover on moon surface satellite images taken by, e.g., NASA lunar reconnaissance orbiter (LRO)

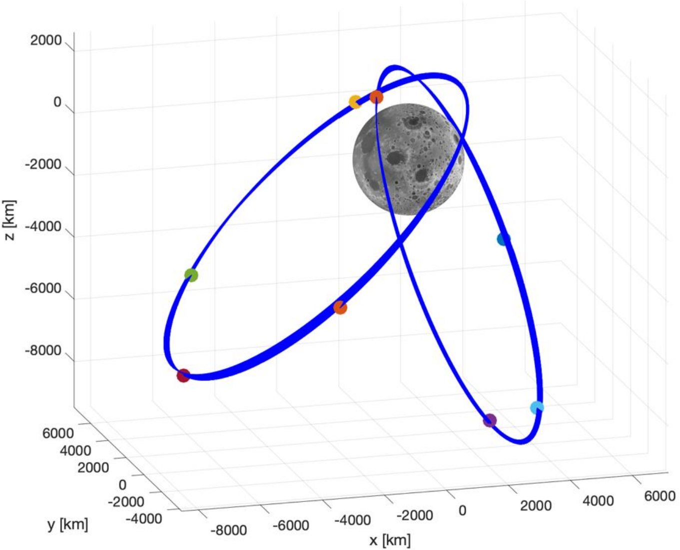


Requirements of LNSS

- Real-time horizontal positioning accuracy less than 40 meters at the lunar South Pole region at any time
  - We need dedicated satellite constellation and accurate orbit and clock determination for the LNSS satellites
- 10 Mbps and more, and hopefully 1 Gbps transmission rate between the moon and the earth
  - We use the LNSS satellites as communication relay satellites using X-band and Ka-band. Optical communication links are also possible choices

LNSS satellite constellation

- Eight-satellite constellation using two elliptical lunar frozen orbits (ELFOs)

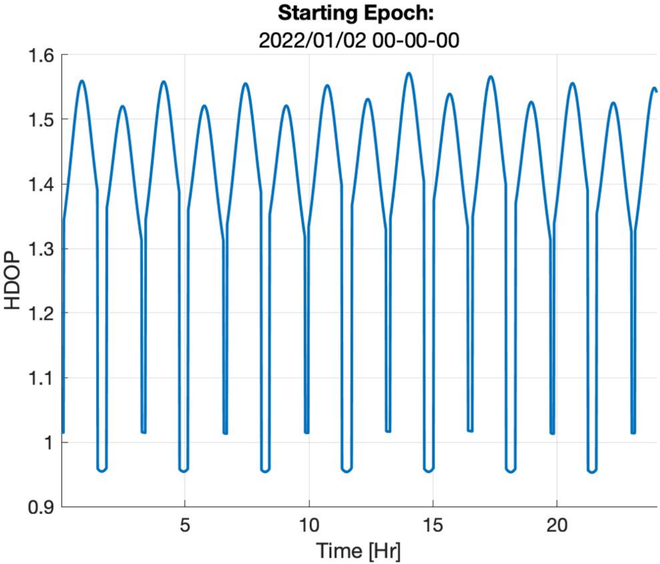


LNSS satellite constellation (cont'd)

- These stable orbits (ELFOs) place the LNSS satellites up above the South Pole region for a long duration

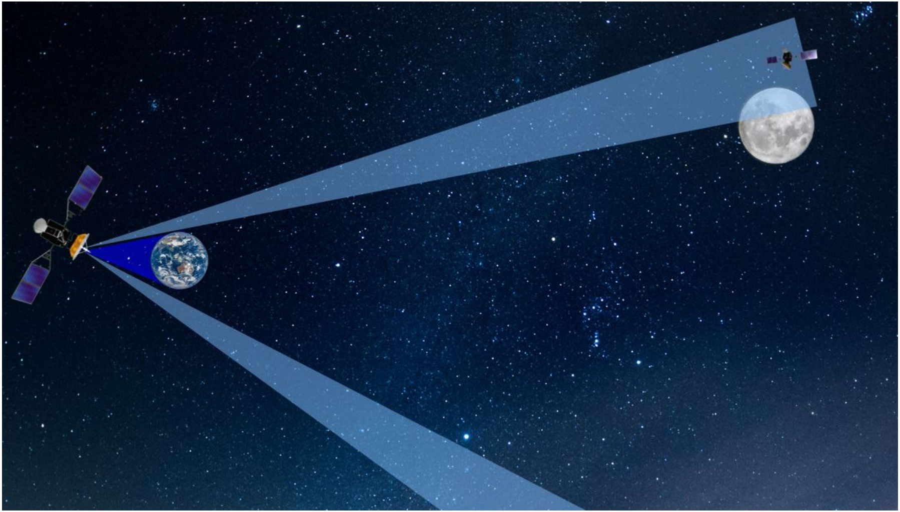
LNSS satellite constellation (cont'd)

- Low horizontal dilution of precision (HDOP). The GPS's HDOP was about 1.2 at Tsukuba space center in Japan



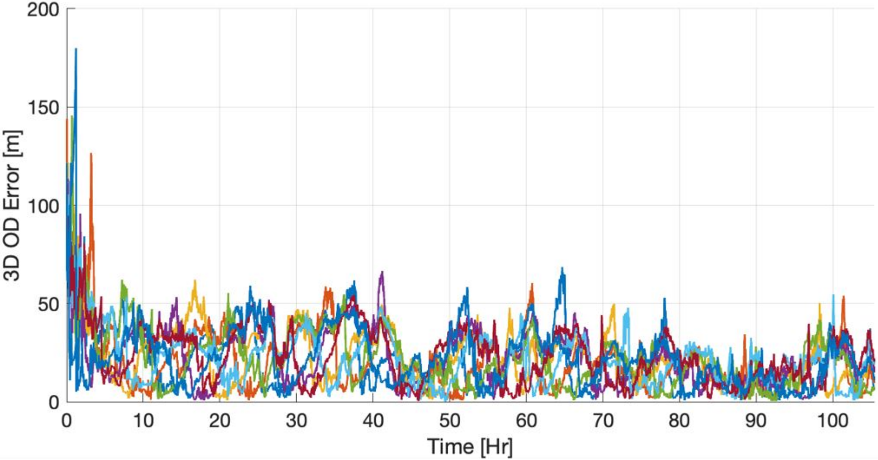
Orbit and clock estimation of LNSS satellites

- GPS and global navigation satellite system (GNSS) navigation using the weak navigation signals



Orbit and clock estimation of LNSS satellites

- GPS navigation accuracy for the eight LNSS satellites with onboard space-borne rubidium atomic clock frequency standard (RAFS) clocks
  - Each color represents each satellite and the RMS values of the orbit and clock estimation errors were 16.5 and 1.4 meters

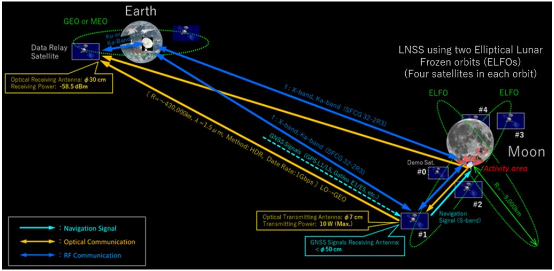


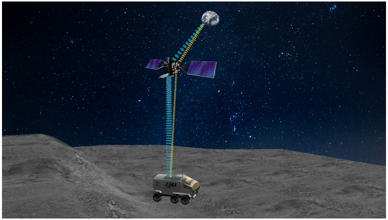
Summary of LNSS

- Requirement: real-time horizontal positioning accuracy less than 40 meters at the lunar South Pole region at any time
  - We have designed the eight-satellite constellation using two ELFOs to achieve low HDOPs at the South Pole region
  - Orbit and clock determination for the LNSS satellites are performed onboard the LNSS satellites using the GPS (GNSS) weak signal navigation technique
  - Orbit and clock information of the LNSS satellites called the ephemerides are frequently updated onboard the satellites, e.g., every five minutes, and broadcasted to lunar surface users
  - Then, we have confirmed that our LNSS achieves the positioning accuracy requirement with a high probability

Communications of LNSS

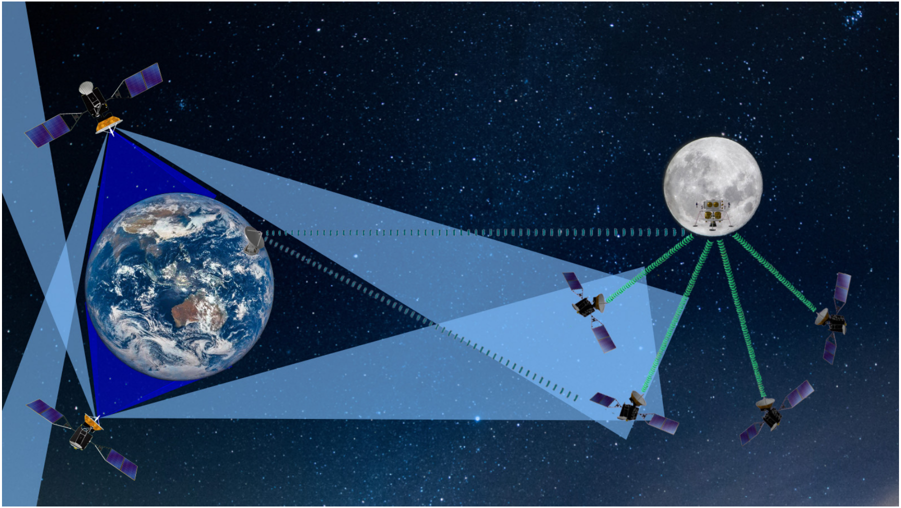
- Requirement: 10 Mbps and more, and hopefully 1 Gbps transmission rate between the moon and the earth
  - 10 Mbps to 1 Gbps from the moon surface to the earth for mission data transmission
  - We use the LNSS satellites as communication relay satellites using X-band, Ka-band, and possibly optical links too





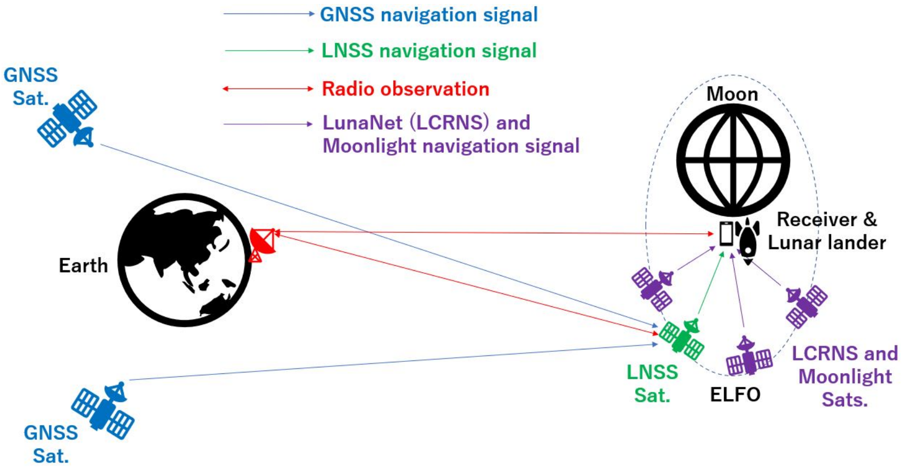
LNSS demonstration mission scheduled in 2028

- Evaluation of the GPS (GNSS) weak signal navigation and our LNSS navigation signals in actual moon environment



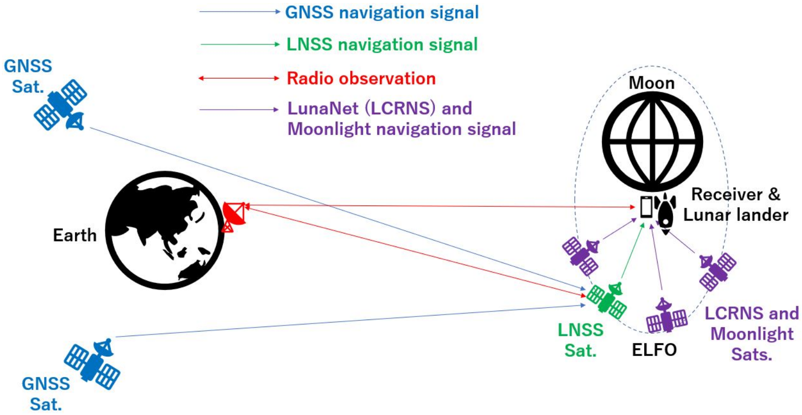
LNSS demonstration mission scheduled in 2028

- One LNSS satellite and one LNSS receiver to be deployed in the ELFO and at the South Pole region, respectively



LNSS demonstration mission (cont'd)

- The ground-truth data of this mission are necessary
  - First challenge is to obtain the ground-truth orbit and clock data of the LNSS satellite flying in the ELFO
  - Second challenge is to obtain the ground-truth position and clock data of the receiver at the South Pole region



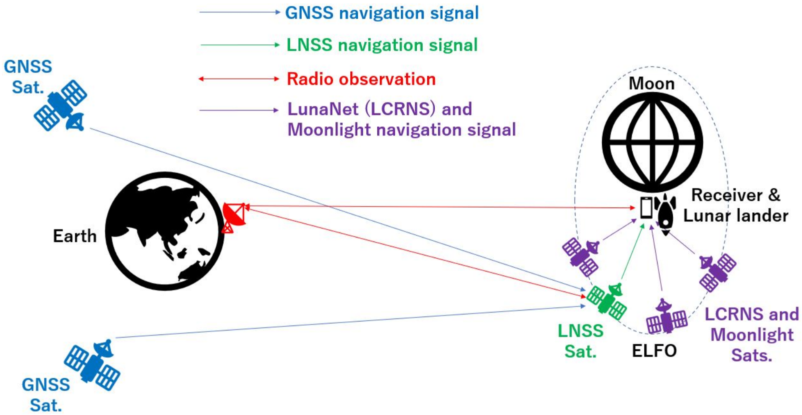
LNSS demonstration mission (cont'd)

- We aim to achieve these ground-truth orbit, position, and clock data by 1 to 3 meter accuracy (the smaller the better)
- The long-term radio observation by earth stations will help us determine the orbit and position, although the clocks of the LNSS satellite and receiver are not accessible by this method
  - The radio observation are the range and range rate (RARR) and the delta differential one-way ranging (DDOR)
- We are checking the time-transfer technique recently proposed for the satellite clock determination*
  - Using the pre-calculated satellite orbit by the radio observation, the satellite clock is estimated by the GPS (GNSS) signals

*Bhamidipati et al., "Design Considerations of a Lunar Navigation Satellite System with Time-Transfer from Earth-GPS", Proc. ION GNSS+2021, 2021, pp. 950-965

LNSS demonstration mission (cont'd)

- As for the clock estimation of the receiver at the South Pole region, no related publications available yet, to our knowledge
- We are investigating the possibility of using NASA's lunar communications relay and navigation system (LCRNS) and ESA's Moonlight to access the receiver clock



Upcoming related lunar programs

- September 2022: US Artemis 1
- 2023-2024: NASA Lunar GNSS Receiver Experiment (LuGRE)
  - GNSS acquisition, navigation, and orbit determination experiments in cis-lunar and moon environment
- 2024: US Artemis 2
- 2024-2027: US LunaNet (LCRNS) Initial Operating Capability
  - Providing communication and PNT for moon
- 2024: ESA Lunar Pathfinder
  - GNSS acquisition, navigation, orbit determination, and communication experiments in the ELFO
- 2025: US Artemis 3
- 2027$\sim$: ESA Moonlight Initial Operating Capability
  - Providing communication and PNT at lunar South Pole
- 2028$\sim$: US LunaNet Enhanced Operating Capability
  - Full coverage for entire moon surface?

Interoperability among different systems

- The GNSS is composed of the GPS (USA), GLONASS (Russia), Galileo (Europe), BeiDou (China), QZSS (Japan), IRNSS (India) and other countries are joining as well
- The interoperability among these systems has been one of the key issues in the GNSS community, which has been quite successful by international efforts
- The interoperability is also the case for the lunar PNT systems under planning such as the NASA's LunaNet (LCRNS), ESA's Moonlight, and our LNSS. I recently heard that Italy and China are also designing the similar systems
- We have been participating in the interoperability discussion at working groups of international organizations such as the International Committee on GNSS (ICG) and the Interagency Operations Advisory Group (IOAG)

Conclusions

- Mission and system overview of our LNSS are presented
- The demonstration mission is currently under planning and scheduled in 2028, which will become the first-ever navigation satellite PNT experiment in the moon environment
- The interoperability will become the key issue and discussion has been ongoing in both multilateral and bilateral forms